The effect of surface heterogeneity on cloud absorption estimates

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This study presents a systematic and quantitative analysis of the effect of inhomogeneous surface albedo on shortwave cloud absorption estimates. We use 3D radiative transfer modeling with gradually complex clouds over a simplified surface to calculate cloud absorption. We find that averaging surface albedo always underestimates cloud absorption, and thus accounting for surface heterogeneity always enhances cloud absorption. However, the impact on cloud absorption estimates is not enough to explain the discrepancy between measured and model-calculated shortwave cloud absorptions.

1. Introduction

The anomalous shortwave cloud absorption, defined as the difference between measured and model-calculated absorptions, has been found on the order of 10 W/m^2. Regardless of the recent intense debates about whether this difference is significant [*Ackerman et al.*, 2003; *O'Hirok and Gautier*, 2003; *Valero et al.*, 2003], there is no doubt that some degree of discrepancy exists in observed and calculated cloud absorptions, and this difference tends to be a bias rather than a random error [*Valero et al.*, 2003]. This excess absorption is not large but any such bias is of concern since radiative transfer models are widely assumed to be sufficiently accurate for climate modeling and remote sensing applications.

Numerous efforts have been made to identify potential sources of this shortwave cloud absorption bias, including from the aspects of sampling issues, measurements uncertainty, cloud inhomogeneity, microphysics optical properties, and aerosols loading [*Barker*, 1992; *Marshak et al.*, 1997; *Valero et al.*, 1997a; *Cess et al.*, 1999; *Knyazikhin et al.*, 2002; *Ackerman et al.*, 2003; *O'Hirok and Gautier*, 2003; *Oreopoulos et al.*, 2003]. Based on high-resolution spectral albedo data along with a state-of-the-art radiative transfer model [*Li et al.*, 2002], it also has been stated [*Li et al.*, 2003] that accounting for the heterogeneity of surface albedo could reduce the systematic difference between measured and modeled cloud absorptions. However, the influence of inhomogeneous surface albedo, if any, has been ignored in most climate models. As a result, up to now, there have been no systematic and quantitative analyses of the effects of surface heterogeneity on cloud absorption estimates. This study aims to provide a thorough analysis to understand how accounting for surface heterogeneity affects cloud absorption, and to examine whether the observed cloud absorption bias could be explained by inhomogeneous surface albedo.

2. Approach

We used the Discrete-Ordinate-method radiative transfer model (DISORT) [*Stamnes et al.*, 1988], a Monte Carlo method [*Marchuk et al.*, 1980], and the Spherical Harmonics Discrete Ordinate Method (SHDOM) [*Evans*, 1998] to calculate cloud absorption. Models were set up with clouds over a checkerboard albedo surface (shown in Fig. 1), where the complexity of clouds increases from homogeneous to broken clouds. The checkerboard surface was changed from the extreme case of black and white albedos, having the largest contrast, to a black and gray pattern, which is closer to measured albedos from the Atmospheric Radiation Measurement (ARM) Program. Cloud properties are defined via cloud optical depth τ and single scattering albedo ϖ_0, and cosine of the solar zenith angle (SZA) is denoted as μ_0.

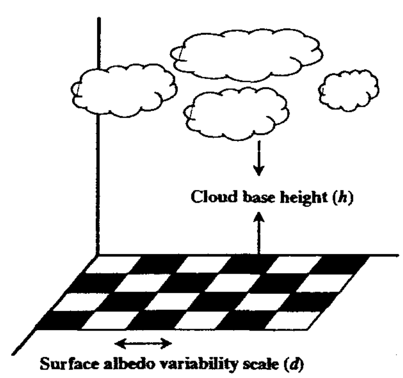

Figure 1. Schematic illustration of model setup.

Based on energy conservation, cloud absorptance A can be computed from reflectance R and transmittance T as

$$A(\alpha) = 1 - R(\alpha) - (1 - \alpha)T(\alpha), \tag{1}$$

where A, R, and T are all functions of Lambertian surface albedo α, and $(1 - \alpha)T$ presents total surface absorption. Note that A, R, and T are also functions of τ, ϖ_0 and μ_0. Since [*Liou*, 2002]

$$R(\alpha) = R_0 + \frac{{T_0}^2 \alpha}{1 - \alpha R^*} \tag{2}$$

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two ends is around 8%. When the scale ratio decreases towards zero, the cloud absorptance is approaching the SIPA estimate. This limiting case of small s, in which the cloud layer is low, and thus most cloud absorption is attributed to photons directly from the underneath surface pixel, is close to the surface independent pixel assumption. On the contrary, cloud absorptance reaches the homogeneous-surface estimate in the limiting case of larger s. Since this case corresponds to a higher cloud base, photons from other surface pixels would have more chances to enter the cloud pixel of interest. As a result, the surface looks gray to the cloud, which is close to the homogeneous-surface assumption.

4. Inhomogeneous clouds

The previous section has demonstrated the effects of surface heterogeneity on cloud absorption for homogeneous clouds. However, observed clouds are rarely uniform without any internal or horizontal variability [*Davies*, 1978]. Hence, we need to understand whether inhomogeneous albedo surface affects heterogeneous clouds in the same way and with a comparable degree of impact. To simulate cloud inhomogeneity, a fractionally integrated cascade model [*Schertzer and Lovejoy*, 1987] was used to generate various cloud structures. For a variety of cloud fractions 50 realizations were produced at a given mean optical depth of 16. These realizations then were used to calculate cloud absorption for $\varpi_0 = 0.99$ and various zenith angles and cloud scales. We find that there is no significantly qualitative or quantitative difference in the effects of surface heterogeneity for fractal clouds rather than homogeneous clouds (figures not shown). In 3D clouds, 5~7% of change in cloud absorption is found between the two limiting cases of SIPA and HS.

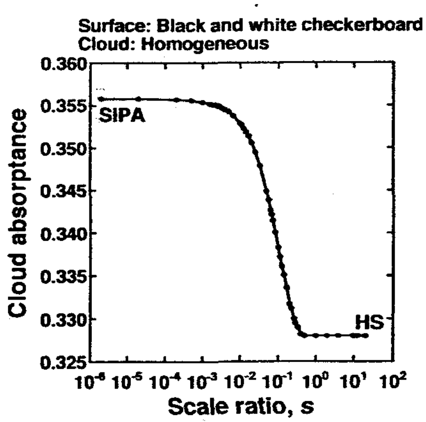

Figure 4. Cloud absorptance as a function of scale ratio s for the "biggest-effect" case: (τ, ϖ_0, μ_0) = (16, 0.99, 1.0). s is the ratio of cloud base height to the scale of inhomogeneous albedo surface. SIPA indicates that cloud absorptance approaches the estimate made by the surface independent pixel assumption in the limiting case of small s. HS shows that the cloud absorptance is toward the homogeneous-surface estimate in the limiting case of large s.

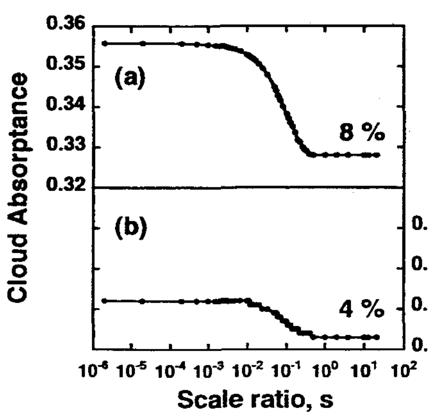

Figure 5. Cloud absorption as a function of scale ratio with an underlying black and white checkerboard surface for (a) the case same as Fig. 4, and (b) the case integrating over various clouds, wavelengths, and solar zenith angles. The percentage indicates the relative bias in percentage between the smallest and largest scale ratios.

5. Inclusions of broadband spectrum, diurnal cycle and various clouds

We have demonstrated how inhomogeneous surface affects single-wavelength cloud absorption for homogeneous and heterogeneous clouds over a black and white checkerboard surface. When we consider all variability of τ, ϖ_0, and μ_0, by defining cloud absorptance as $A(\tau, \varpi_0, \mu_0, \alpha)$, the overall cloud absorption $\langle A \rangle$ can be computed by

$$\langle A \rangle = \int_{\varpi_0} \int_{\mu_0} \int_{\tau} A(\tau, \varpi_0, \mu_0, \alpha) \cdot P_\tau(\tau) P_{\mu_0}(\mu_0) P_{\varpi_0}(\varpi_0) d\tau d\mu_0 d\varpi_0, \quad (7)$$

where P_τ, P_{μ_0}, and P_{ϖ_0} represent the probability density functions of τ, μ_0, and ϖ_0, respectively. P_τ was estimated from simulations of the cascade model with a sample mean of 16. P_{μ_0} was approximated by equal weights at zenith angles of 30, 45 and 60°. For P_{ϖ_0}, we divided the solar spectrum into five intervals to find weighting factors for the corresponding averaged single scattering albedo. Then, using a simple quadrature rule, the approximated cloud absorption could be obtained.

The resulting broadband cloud absorptance over a black and white checkerboard surface is shown in Fig. 5(b). For comparison, the biggest-effect case for homogeneous clouds is plotted in Fig. 5(a). The bias due to the change of scale ratio reduces to less than 4% after considering different clouds, a diurnal cycle, and a broadband spectrum. Note

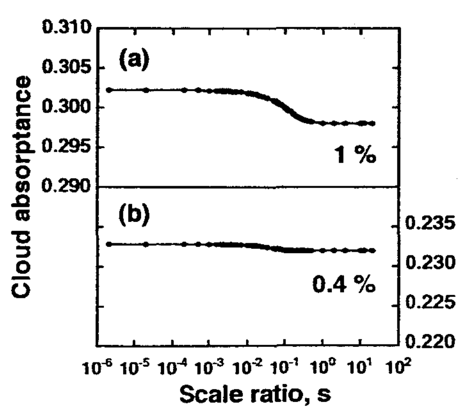

Figure 6. Same as Fig. 5, but with a black (albedo of 0) and gray (albedo of 0.5) checkerboard surface in which the albedo is closer to the ARM measurements.

The Effect of Surface Heterogeneity on Cloud Absorption Estimates

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Popular Summary

"Enhanced shortwave cloud absorption" (the discrepancy between measured and model-calculated cloud absorptions) has been a major concern in the climate community. The reason is that this excess absorption is always a bias on the order of 10 W/m^2 rather than a random error, and in turn, may have significant impact on climate modeling and remote sensing application. Among various explanations for this bias, it has been stated that taking surface heterogeneity into account could eliminate this discrepancy. However, the influence of inhomogeneous surface albedo, if any, has been ignored in most climate models. As a result, up to now, there have been no thorough analyses of the effects of surface heterogeneity on cloud absorption estimates.

This study presents a systematic and quantitative analysis of the effect of inhomogeneous surface albedo on shortwave cloud absorption estimates. We provide both theoretical proof and numerical calculations to demonstrate that the use of an averaged surface albedo always underestimates cloud absorption. Thus, accounting for surface heterogeneity always enhances cloud absorption. However, the impact of inhomogeneous surface albedo (less than 0.5%, or ~1 W/m^2) is negligible and cannot explain the enhanced shortwave cloud absorption.